Predictability Limitations of Long-Range Sound Propagation

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LONG-TERM GOAL

Our long-term scientific goal is to understand the basic physics of low-frequency long-range sound propagation in the ocean, and the effects of environmental variability on signal stability and coherence. We seek to understand the fundamental limits to signal processing imposed by ocean variability to enable advanced signal processing techniques, including matched field processing and other adaptive array processing methods.

OBJECTIVES

The principal objective of our ongoing effort is to develop a theory of acoustic fluctuations in long-range propagation that correctly accounts for measurements. This objective is motivated by the failure (as reported by Colosi *et al*, 1999) of traditional approaches (see, e.g., Flatté *et al*., 1979) to the study of wave propagation in random media (WPRM) to predict measured time spreads and intensity statistics in recent long-range underwater acoustic experiments. Work to date strongly suggests that acoustic fluctuations are to a surprisingly large degree controlled by a property (the ray-based stability parameter α or the asymptotically equivalent mode-based waveguide invariant β) of the background sound speed profile, rather than details of the sound speed perturbation. As a result, much of the recent theoretical work has been motivated by a desire to understand what wavefield properties are controlled by α or β.

APPROACH

The group in Miami (M Brown, F J Beron-Vera, I Udovydchenkov and I Rypina) has employed a combination of ray- and mode-based theory, combined with PE simulations, to study and quantify acoustic fluctuations. Much, but not all, of the mode-based theory is based on an asymptotic analysis, as this provides a direct link to the ray-based analysis. Similarly, much, but not all, of the ray-based analysis makes use of action-angle variables, as this provides a direct link to the mode-based analysis. Another crucial connection between the ray- and mode-based analyses derives from the asymptotic equivalence of the ray stability parameter α and the modal waveguide invariant β. Throughout the past year we have continued to extend relevant theoretical developments, but we have prioritized work involving the application of theoretical results to the analysis of measurements made as part of the

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14. ABSTRACT
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recent LOAPEX propagation experiment. Specific topics/questions, which have been investigated by the PI during the past two years, are listed in the following section.

WORK COMPLETED

1. Ray-mode duality

It has been shown (Brown *et al.*, 2005) that the ray-based stability parameter α is asymptotically equivalent to the mode-based waveguide invariant β. Further, in the same paper it is shown that a remarkable number of properties of wavefields and their stability are controlled by this parameter.

2. A simple transformation eliminates PE errors

A simple transformation has been discovered (Rypina *et al.*, 2006) which allows solutions to the Helmholtz equation to be generated by solving (in the transformed environment) the parabolic wave equation. There are several caveats which will not be discussed here; in spite of these caveats, the result is somewhat surprising and extremely useful.

3. *Effective ray widths in inhomogeneous media*

Under typical deep ocean propagation conditions at ranges of approximately 100 km or more there are two contributions to the effective width of a ray. The first is the diffractive contribution, the Fresnel zone width. The second is a scattering-induced, or micromultipathing, contribution. In Rypina and Brown (2007) approximate analytical expressions for both contributions are derived in an environment consisting of a stratified background on which a small-scale perturbation, due for example to internal waves, is superimposed; both contributions are shown to be controlled by α. In the same paper it is shown that theoretical predictions agree well with travel time sensitivity kernel (TSK) (Skarsoulis and Cornuelle, 2004) calculations.

4. Modal group time spreads

Modal group time spreads in an environment consisting of a stratified background on which a small-scale perturbation, due for example to internal waves, is superimposed have recently been investigated (Udovydchenkov and Brown, 2007). In this paper it is shown that that there are three contributions to the time spread - the reciprocal bandwidth, a deterministic dispersive contribution and a scattering-induced contribution - and that the dispersive and scattering contributions are controlled by β. This work provides a foundation for much of the LOAPEX experiment data analysis effort described below (see 7.).

5. Beam dynamics

The dynamics of directionally narrow acoustic beams have recently investigated by Beron-Vera and Brown (2007). Both the spatial and temporal spreading narrow beams have been shown to be controlled by α (or its mode equivalent β). This conclusion is supported by both ray- and mode-based analyses.

6. Resonant scattering and resonance widths

A correct, but not widely utilized, description of the mechanism underlying sound scattering in a waveguide (e.g., mode coupling) is resonant scattering. Resonances are excited between the background rays, which are periodic in range, and periodic structures in the sound speed perturbation. For a narrowband (in horizontal wavenumber) perturbation only a small number of resonances are excited, while for a broadband perturbation many resonances are excited. As a first step towards better understanding and quantifying this process, a general expression for resonance widths has been derived (Rypina et al., 2007). Resonant scattering will be further explored in future work.

7. LOAPEX analysis

Analysis of LOAPEX measurements is now well underway, both at RSMAS and elsewhere, especially APL/UW. The work at RSMAS has so far been closely linked to the modal group time spread work described in 4., above. This work, which involves many collaborators at APL/UW and SIO, is currently being written up. Agreement between measurements (after suitable mode processing) and theoretical predictions is quite good.

RESULTS

Although our goal of developing a theory of acoustic fluctuations in long-range propagation is not yet complete, significant progress has been made. The forward scattering physics are much better understood than was the case a few years ago. An important result of the PI's work over the past few years is conceptual: the forward scattering of sound — by internal-wave-induced perturbations, for example — is largely controlled the background sound speed structure. Thus, sound scattering in environments with identical internal-wave-induced sound speed perturbations but different background speed structures may be very different.

IMPACT/APPLICATION

Our work is contributing to an improved understanding of the basic physics of low-frequency long-range sound propagation in the ocean, and the associated loss of signal stability and coherence imposed by environmental variability. This knowledge contributes to an understanding of the limitations of advanced signal processing techniques, such as matched field processing.

TRANSITIONS

Our results are being used to interpret (reinterpret, in some cases) data collected in long-range propagation experiments, e.g. SLICE89, AET, SPICE04 and LOAPEX. We are unaware of transitions to system applications.

RELATED PROJECTS

The PI and collaborators listed above actively collaborate with the NPAL (North Pacific Acoustic Laboratory) groups at SIO (P. Worcester, W. Munk, B. Cornuelle, M. Dzieciuch), APL/UW (J. Mercer, B. Dushaw, B. Howe, R. Andrew, F. Henyey and M. Wolfson) and NPS (J. Colosi).

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